ELECTRONIC MATERIALS RESEARCH LABORATORY

THE UNIVERSITY OF TEXAS

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NO OTS

Superconductive Frequency
Control Devices
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Second Quarterly Report
1 October 1962 to 31 December 1962

U. S. Army Signal Research and Development
Laboratory

The object of the research is to investigate the performance of superconductive tank circuits and to arrive at design criteria of a tunable superconductive frequency control device.

By

William H. Hartwig
Project Director

EMRL Report No. 121

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PURPOSE

1. General

Previous work of this laboratory has established that loaded Q's in excess of 10^5 can be obtained with superconductive resonant tank circuits. Coupling, radiation, and dielectric dissipation may dominate the ohmic loss in determining Q at HF and VHF frequencies. Such circuits are tunable over a considerable range of Q and frequency. Design of tunable superconducting frequency control devices requires consideration of frequency-temperature effects, means of coupling and tuning, maintenance of a cryogenic environment, geometry, and microphony. More important, however, is a better understanding of the conduction, energy storage, and energy dissipation processes in materials with exploitable properties. The purpose of this investigation is to evaluate the design criteria while carrying out the basic studies.

2. Detailed Requirements:

a. Using bulk and thin films, study the residual impedance of pure metals and alloys with zero field transitions above $4.2^{\circ}K$ as a function of

(1) Frequency and temperature and

(2) Signal level and external magnetic field.

b. Using superconducting tank circuits in an oscillator evaluate their performance as a function of

(1) Temperature in the operating range,

(2) Configuration and means of coupling, and

(3) An external magnetic field.

c. Investigate and catalog the physical properties of materials with particular reference to their use in high frequency superconductive circuits.

d. Direct the studies outlined under a., b., and c. above so as to make them of maximum use in establishing a rational basis for the design of tunable superconductive frequency control devices with predictable performance.

I. ABSTRACT

During the second quarter improved experimental apparatus was assembled and calibration was begun. An improved system for measureing Q at greatly reduced coupling was assembled incorporating a very sensitive receiver. Components were fabricated to permit precise control of temperature in the dewar with provisions for more accurate coupling variation.

Theoretical work on the effects of an external magnetic field continued. Measurements made during the first quarter of this contract and the last quarter of the previous one are explained in terms of the intermediate state of hollow superconducting cylinders.

Studies of inductance calculation proceeded to the point where the solution for a coaxial inductor in a closed cylindrical shield was obtained. The geometry is for current strips of zero thickness.

II. PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

Two papers have been accepted for publication. The first entitled "Superconducting Resonance Circuits" will be presented by the project director at the 1963 International Solid-State Circuits Conference at the University of Pennsylvania, February 22, 1963. A digest of the paper entitled "Q Measurement of Superconducting Tanks" has been accepted by Electronics magazine to appear in an early issue.

The project director attended the Electron Devices meeting in Washington D. C. on October 25, 26, and 27.

On November 29 Dr. E. Hafner and Mr. M. W. Woodruff of USASRDL visited the University of Texas. All phases of the project were discussed.

III. FACTUAL DATA

A. No residual resistance measurements were made during this quarter. Efforts were confined to theoretical analysis of residual resistance, equipment calibration and experiment design.

B. Interpretation of Previous Experiments

Q was observed to decrease proportional to the square of an external D. C. magnetic field on each of the circuits tested to date. At, $H_o = 0$, the Q was limited by coupling or other losses. As shown in figures 7 and 8 of the previous Quarterly Progress Report[1], the residual resistance increased about two orders of magnitude over a range of magnetic field of 100 to 1000 gauss. Below the lower value the residual resistance change was masked by the dominating temperature independent losses. Very little, if any, discontinuity at the normal transition value for pure lead was observed. Instead the residual resistance continued to increase as H_o^2 until the D. C. magnetic field was nearly twice the critical field for pure lead at 4.2^{o}K, namely about 600 gauss.

The frequency shift due to surface reactance effect was very small. The complete explanation for the change in Q is not easily achieved, since several factors appear to be significant. It has been known for some time that a hollow superconducting cylinder in a D. C. magnetic field placed normal to the axis will be in the intermediate state.

Gittleman[2] has shown that penetration of the field occurs well below 0.5 H_c, which would be expected for a solid cylinder. Serin, Gittleman, and Lynton[3] have shown that the value of H_o required for penetration into a hollow cylinder depends upon the ratio of the inner to outer diameters.

From the First Law of Thermodynamics

$$TdS = dU + IdH_o$$

where I = total magnetic moment of the sample. (See E. C. Stoner, Phil. Mag. 23, 833, 1937).

T = absolute temperature

S = entropy

U = internal energy,

H_o is the applied field.

The Helmholtz free energy is

$$F = f_o(T)V - \int_0^{H_o} IdH_o$$

where $f_o(T)$ is the free energy <u>per</u> <u>unit</u> <u>volume</u> at $H_o = 0$,

V is the volume of the superconductor

then

$$f_{on} - f_{os} = H_c^2/8\pi \quad \text{where } H_c \text{ is the critical field.}$$

The difference in the total free energy for a solid cylinder is

$$F_n - F_s = \left[(H_c^2/8\pi) - (H_o^2/4\pi)\right] V$$

where H_o is transverse to the axis.

Thus the total free energy for the normal cylinder equals that for the superconducting cylinder when

$$H_o = H_c/\sqrt{2}$$

The cylinder will be in an equilibrium state of superconductivity when F_s F_n or H_o 0.707 H_c. The transition to completely normal conductivity occurs when $H_o = 0.707\ H_c$, unless an intermediate state can exist where the total free energy is a minimum.

For a hollow cylinder the difference in free energy is

$$F_n - F_s = \left[(H_c{}^2 V_H/8\pi) - (H_o{}^2 V_s/4\pi)\right]$$

where V_s= volume of the solid cylinder having the same outer radius as the hollow one. The second term in independent of the size of the hole. The first term is temperature dependent and becomes smaller as the shell thickness decreases at a given T. Clearly as V_H decreases the difference in F_n and F_s can become zero for lower values of H_o. As a consequence for small values of the inner radius, b, $F_n = F_s$ for $H_o > H_c/2$, the value at which Peierls(4) has shown the intermediate state appears. For thin-walled cylinders the intermediate state will occur at $H_o < H_c/2$ according to the equation

$$F_n - F_s = \left[(H_c{}^2/8\pi) - (H_o{}^2/4\pi)(a^2/a^2-b^2)\right] \quad V_H$$

where a is the outer radius. The value of H_o at which the field can be expected to penetrate the shield is H_{oe}, or for $F_n = F_s$.

$$2(H_{oe}/H_c)^2 = 1 - (b/a)^2 \approx \left[2(a-b)/b\right]$$

In the case of a shield can the ratio b/a is very nearly unity, hence one would expect some effect upon Q from very low fields. For example, the shield used has 0.005" lead foil lining a shell 2-3/4" ID. Assuming $H_c \approx 600$ gauss,

$H_{oe} = 36$ gauss. This value is above the earth's field but indicates a thin-film shield is likely to be unsatisfactory. The authors further reason that the intermediate state will certainly occur for a field less than the one for which $F_n = F_s$, since the normal state has a lower free energy than the superconducting state. For the shield geometry used, where the bottom is flat and the corners not rounded, the onset of the intermediate state will probably occur at some value less than the H_{oe} calculated.

Parmenter[5] has shown that superconductivity may persist, through the intermediate state, in a magnetic field much higher than H_c. He indicated a possible association of the quantity $(\lambda/\xi)H_o$ with the so-called Kunzler field H_K. λ is the London penetration depth and ξ is the Pippard coherence distance. The Kunzler field is an order of magnitude or more above H_o (for pure materials) and applies to certain superconducting alloys and compounds. In view of the nature of the material used in our experiment, it is felt likely that the observed decrease in Q above H_c may be explained on this basis.

Since the circuit does not jump abruptly from the superconducting to normal state at H_c, it is inferred that portions of the circuit retain their superconductivity until about $2H_c$. This is probably a value dependent upon the geometry.

C. Molded Circuits

Efforts to mold circuits in glass which would hopefully retain the fire-polished smoothness of the glass tubing have

so far resulted in disappointment. Due to the differences in thermal expansion, molded inductor coils always have severely constricted cross sections at corners. The metal does not remain in contact with the glass below the solidification temperature so that, upon shrinking, the smoothness is not preserved.

D. Theory of Tunable Circuits in a D. C. Field

Several practical and scientific areas may be profitably exploited with a superconductive resonant circuit in a D. C. magnetic field which employs a tuning slug and provisions to vary temperature. This section describes the theoretical basis and experimental documentation for future phases of this research. In summary the following set of conditions applies to the circuits under study.

(1) A very low D. C. magnetic field will penetrate the shield without apparently destroying its usefulness as a radiation barrier.

(2) The surface resistance increased as H_o^2, which provides for a novel means of varying circuit bandwidth.

(3) Surface reactance varys in a similar manner. It can be studied independently by obtaining a frequency shift of a superconducting tank incorporated in an oscillator.

(4) The resonant frequency may be readily changed in an evacuated circuit using a superconducting slug.

(5) The superconducting slug may be of the same or different material from the remainder of the circuit.

(6) The effect of an external magnetic field on the Q is several orders of magnitude greater than the effect on the resonant frequency.

(7) D. C. conductivity measured on the same material as the circuit can yield data on the ratio of number of normal electrons to the effective mass, if relaxation time is known.

(8) Relaxation time may be determined from residual resistance measurements in the absence of a magnetic field.

(9) Combined with measurements for surface resistance and reactance it is possible, in principle, to perform a completely consistent set of experiments which will determine many physical properties of the normal electrons such as relaxation time, effective mass, density of free electrons, Fermi velocity, and mean free path.

1. Source of a D. C. Magnetic Field

The previous experiments involved the use of a large electromagnet to provide the field. This is seen in figure 3, page 5, of the Final Report[6], Contract No. DA-36-039-SC-87312. A superconducting magnet can be incorporated in the circuit consisting of a set of coils located outside the shield or between two shields suitably arranged. In this way a superconducting frequency control device incorporating D. C. magnetic field control of Q could be fabricated as a self contained unit. Novel arrangements of such coils, some or all carrying persistent currents, would provide the device with features which are unavailable in any other frequency

control device. The extension of the concept to signal filters, wave traps, interference filters, delay lines, and other superconductive devices is indicated.

2. Use of a Tuning Slug

Previous experiments with tuning slugs reported in the Final Report[6] of Contract DA-36-039 SC-87312 and tabulated in Table 5, page 9 show that large frequency changes are possible. It appears that the change in frequency will be accompanied by a reduction in Q. The dependence of Q change upon frequency change needs further study. Experience, so far, points to a problem of surface current density in the slug being higher than on the inductor if the slug is large. The transformer action of the slug, behaving as a single shorted turn, may introduce excessive loss.

Since the tuning slug may be fashioned from any material, it can be used to study surface impedance effects in the same way that Pippard, Chambers, and many others have studied superconductors. Of particular interest to the project is the saving which may come from the use of slugs from a variety of hard and soft superconducting materials and alloys. The cost of a superconducting resonant circuit, with a shield, in the frequency range of interest to the project, is necessarily high.

3. Effect of Combinging D. C. Field, Slug Tuning, and Variation in Coupling

As developed in the First Quarterly Progress Report[1] variations in coupling and choice of magnetic or electrostatic coupling makes possible a third independent frequency and/or Q control. The equations developed in Report No. 1,[1]

Section III. A, ignored the possibility of Q variation by changing the terminating resistance of either or both coupling probes. For example, the derivation of the effect of coupling upon the resonant frequency for a capacitive probe was simplified by ignoring the effect of a terminating resistance. It is very small compared to the coupling reactance. Admitting now the possibility of variation in the resistance (of either a capacitive or an inductive probe), one sees that Q can be changed without a change in frequency. Furthermore the simultaneous change of coupling and termination could be incorporated, providing the effects upon the external circuit could also be compensated for.

In summary the following effects are possible.

Method	Approximate Change in Q	Approximate Change in frequency
Magnetic field	Several orders of magnitude	1% or less
Slug	An order of magnitude	less than 100%
Coupling	An order of magnitude	10% or less

By combining these effects in various ways, it is clear a superconductive frequency control device is capable of a large change in both frequency and Q. In addition, a change in only one is possible with the accompanying change in the other being cancelled by suitable compensation.

4. Theory as a Guide to Experiemtns

A careful study of the theories of superconductivity, the calculation of inductance, and the refinement of superconductive circuit theory are all needed for a rational design of superconductive frequency control devices and systems. Within the frequency range of interest, the London two-fluid model has been assumed to hold. This leads to the residual resistance equation in terms of frequency, relaxation time, and reduced temperature.

$$R/R_n = \sqrt{\frac{\left[\omega\tau\ t^4/(1-t^4)\right]}{1+\omega^2\tau^2\left[t^4/(1-t^4)\right]^2} \qquad \left[\sqrt{1+\omega^2\tau^2\left[t^4/(1-t^4)^2\right]} - 1\right]} \qquad (1)$$

This equation has been plotted versus $\omega\tau$ using reduced temperature as a parameter. Q measurements can be used to determine relaxation time by employing these curves, providing frequency and reduced temperature are known. A measurement of D. C. conductivity of the normal state below T_c will provide a measure for $n\tau/m^*$, where <u>n</u> is density of electrons and <u>m*</u> is the effective mass. The equations of surface impedance developed by Dresselhaus and Dresselhaus[7] can be solved for the change in surface resistance and surface reactance due to either a transverse or a longitudinal magnetic field. These equations are:

$$\Delta Z_{L,Cl} = \frac{2\pi i\omega^2\omega_n{}^2\omega_c{}^2\ell^{-5}}{5C^4\ F^3(K_C+i\lambda^{-1})} + \mathcal{O}(H_o{}^4) \qquad (2)$$

$$\Delta Z_{T,Cl} = 4\Delta Z_{L,Cl} + \mathcal{O}(H_o{}^4) \qquad (3)$$

Where: $K_C = \left[-(1/\lambda^2) + (\omega^2/c^2) - i\omega\omega_n^2(\bar{\tau}/c^2)\right]^{\frac{1}{2}}$,

$F^2 = (3h^2/5m^2)(3N/8\pi)^{2/3}$, $\omega_n^2 = (4\pi Ne^2/m)$, $\bar{\tau} = (\tau/1+i\omega\tau)$,

$$\bar{\ell} = v_F\tau(1+i\omega\tau)^{-1},\ \omega_C = eH_o(0)/m^C,\ \lambda = (c/2e)\sqrt{m/\pi N_S} \tag{4}$$

and: τ is the relaxation time, ω is the frequency, v_F is the Fermi velocity, $H_o(0)$ is the D. C. magnetic field at the surface, C is the velocity of light, e is the electronic charge, m is the effective mass, N is the normal electron density at room temperature, and λ is the penetration depth. It should be noted that the "cl" subscript stands for the classical case, as opposed to the anomalous case.

The task now is to manipulate these equations so as to yield relations for both the resistance and the reactance. This has been done and yields the following equations:

$$\frac{\Delta R}{R_n} = -\frac{24\pi h^2e^2H_o^2(0)r^{\frac{1}{2}}\omega^{\frac{1}{2}}\sigma n(1-t^4)^{\frac{1}{2}}}{25m^4c^4}\left(\frac{3N}{8\pi}\right)^{2/3}\left(\sqrt{1+\omega^2\tau^2\left(\frac{t^4}{1-t^4}\right)^2} - 1\right)^{\frac{1}{2}} \tag{5}$$

$$\frac{\Delta X}{X_n} = \frac{48\pi h^2e^2H_o^2(0)\tau^{\frac{1}{2}}\omega^{\frac{1}{2}}\sigma n(1-t^4)^{\frac{1}{2}}}{25\sqrt{2}\,m^4c^4}\left(\frac{3N}{8\pi}\right)^{2/3}\left(1 - \frac{1}{\sqrt{2}}\sqrt{\sqrt{1+\omega^2\tau^2\left(\frac{t^4}{1-t^4}\right)^2}+1}\right) \tag{6}$$

For temperatures only slightly below the transition temperature, equation (5) can be considerably simplified. At this temperature and a frequency in the megacycle range, the product $\omega^2\tau^2(t^4/1-t^4)$, is considerably less than unity. We can thus expand the radical as:

$$\sqrt{1 + \omega^2\tau^2\ (t^4/1-t^4)^2} \simeq 1 + \tfrac{1}{2}\omega^2\tau^2\ (t^4/1-t^4)^2 \tag{7}$$

Leaving:

$$\frac{\Delta R}{R_n} \approx - \frac{3(8\pi)^{1/3} e^2 H_o^{\,2}(0)(3N)^{2/3} \sigma_n \tau^{9/2} \omega^{3/2} h^2}{25\sqrt{2}\, c^4 m^4} \quad \frac{t^4}{\sqrt{1-t^4}} \tag{8}$$

Now let us consider the significance of these equations. We note that the combination of these equations will yield several things. The relaxation time may be obtained directly from either

$$\sigma = (Ne^2\tau/m) \tag{9}$$

(9) or (1) as a function of temperature. This information may then be used in either (5) or (6) to extract the effective mass. If (9) is used, some error will be introduced in that a constant effective mass would have to be assumed to get values of τ. It is also possible to completely eliminate either σ_n or τ from equations (5) and (6). This is demonstrated below with the reduced form of (5), equation (8).

$$\frac{\Delta R}{R_n} \approx - \frac{(8\pi)^{1/3}(3)^{5/3} h^2 \sigma_n^{\,11/2}\, m H_o^{\,2}(0)}{25\sqrt{2}\, c^4 e^7 (N)^{23/6}} \quad \frac{t^4}{\sqrt{1-t^4}} \tag{10}$$

or:

$$\frac{\Delta R}{R_n} \approx - \frac{(8\pi)^{1/3}(3)^{5/3} h^2 H_o^{\,2}(0) e^4 \tau^{11/2} N^{5/3}}{25\sqrt{2}\, c^4 m^5} \quad \frac{t^4}{\sqrt{1-t^4}} \tag{11}$$

Each of these equations presents both advantages and disadvantages. Equation (10) completely eliminates the necessity of determining τ, but is likely to give a large error in the

calculation of m. This is realized from the fact that the estimation of N may be quite inaccurate. Thus if this error is raised to the 23/6 and then squared to get m, the final error in m may be extremely large. The second equation eleiminates conductivity measurement, but requires determination of τ by (1). In this case, however, the error in N is reduced by the cube root, and error in τ is only raised to the 1.1 power.

One might also ask why an expression for reactance at zero D. C. magnetic field was not derived. The reason obviously is the low temperature dependence of the circuit reactance. This would mean that the shrinkage of the circuit and other factors would prohibit the extraction of any useful data.

Assuming that we are able to determine both τ and σ_n with some degree of accuracy, then we should be able to determine m to a very close approximation. This may be seen by the "m" dependence of the equations. Both equations (5) and (6) are proportional to m^{-4}. Thus, in finding m, the total error is raised to the $\frac{1}{4}$ power.

It should be noted that the Dresselhaus equations which have been considered thus far are all for the longituditudinal case. The equations for the transverse case are precisely the same, except for a factor of four. However, complications may arise in the experimental application of the theory for the transverse case. The correlation of the theory and a particular experimental geometry will next be considered.

Consider a superconducting resonant circuit with cylindrical geometry. Such a circuit is shown in Figure 1.

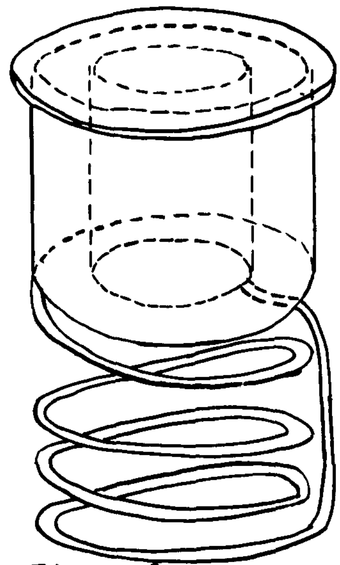

Figure 1

The circuit may be divided into two parts with respect to the direction of current flow. If we neglect the region near the junction of the capacitor and inductor, all the current in the capacitor flows in an axial direction. If we neglect the portion of the inductor which gives it its "slope", all of its current flows circularly in planes parallel to H_o. First consider the inductor. As stated above, the component of current in the axial direction will be neglected and each loop of the coil will be replaced by a short cylinder which has the same surface area per unit length as the loop. Now since the coil is open, we must show the field penetrating the entire area of the cylinder, even though it is superconducting.

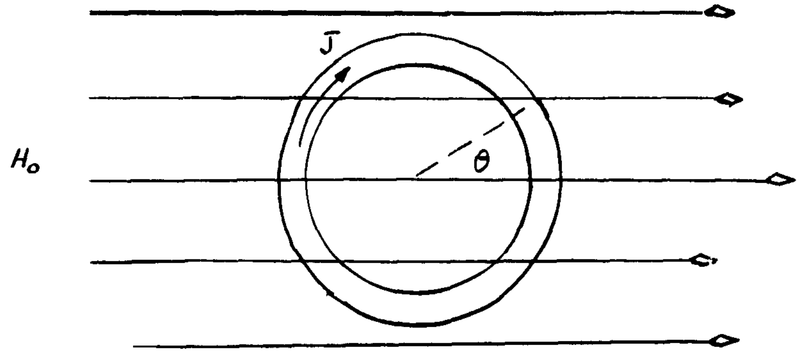

Figure 2

The current flows in a circle, so that parts of it are perpendicular to the field and parts are parallel. Thus the field is described by the following equations.

$$H_o = H_L = -H_o \sin \qquad H_r = H_T = H_o \cos \tag{12}$$

Now:

$$\Delta Z_L = KH_L^{\,2}, \qquad \Delta Z_T = 4KH_T^{\,2} \tag{13}$$

$$\therefore \quad \Delta Z_L = KH_o^{\,2}\sin^2, \qquad \Delta Z_T = 4KH_o^{\,2}\cos^2 \tag{14}$$

In an experiment, what we see is the average impedance of the coil. We must therefore average over the circle.

$$\Delta Z_L = (K/2)H_o^{\,2}, \quad \Delta Z_T = 2KH_o^{\,2} \tag{15}$$

Thus the impedance change in the inductor loop is:

$$\Delta Z = (5/2)KH_o^{\,2} \tag{16}$$

Now consider the capacitor plates. If we assume that the capacitor is in full superconductivity, all flux will be excluded from the interior so that the entire field is transverse.

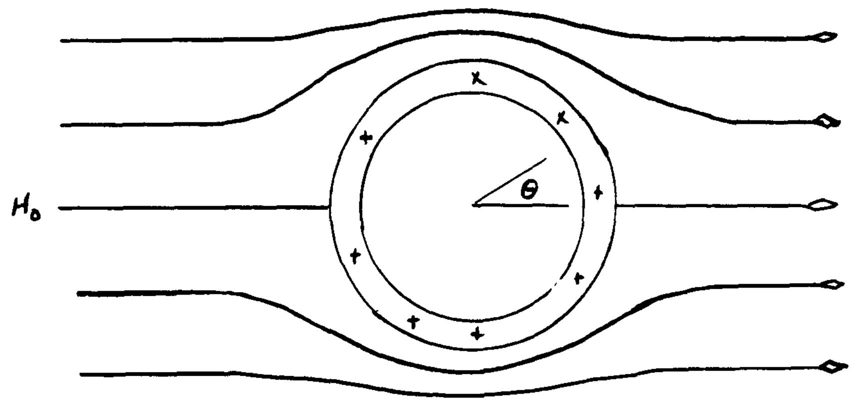

Figure 3

We note, however, that the magnitude of the surface magnetic field varies from zero at 0 degrees to $2H_o$ at 90 degrees. Thus:

$$H_T = 2H_o \sin \quad , \quad H_T{}^2 = 4H_o{}^2 \sin^2 \tag{17}$$

The average value of the change in impedance over the surface is:

$$\Delta Z_T = 2KH_o{}^2 \tag{18}$$

This applies only to the outer capacitor plate. Since we have assumed full superconductivity, the inner capacitor plate is shielded from the field and has no change in impedance.

It should be remembered that these impedances are per unit length per unit width. Therefore, assuming that the equivalent coil cylinder has a width "b" and a circumference "c", we get the change in impedance of the whole coil by:

$$\Delta Z_{coil} = (nC/b)(5/2)\ KH_o{}^2 \tag{19}$$

(Where n is the total number of turns.)

Assuming a length "d" and circumference "f" for the outer capacitor:

$$\Delta Z_{cap} = (d/f)\ 2KH_o{}^2 \tag{20}$$

Now the resistance of the coil is much greater than that of the capacitor plates, so that only one need be considered in a particular case.

It has been assumed in this analysis that the entire circuit is wholly in superconductivity. It is possible that this is not so. Since the cross section of the coil is circular, the maximum field at its surface is $2H_o$. The coil thus goes into the intermediate state at $H_o \leq H_c/2$. The maximum field at the surface of the outer capacitor shell is also $2H_o$. Thus, we would expect the capacitor to go into the intermediate state at approximately the same point.

E. <u>Calculation of Inductance</u>

This phase of the research is nearing completion. A rapidly converging solution using a Green's function has been derived for the shielded current sheet, current strips, and round wires. Present efforts are on the perturbation due to changes in skin depth of the surface current. In addition, a separate solution for the effect of a coaxial superconducting tuning slug is being written.

When these solutions are available they will serve several useful purposes. The change in inductance from the normal to the superconducting state can be estimated by the change in skin depth. This will result in a change in frequency which can be measured. The effects of dimension changes due to thermal contraction can also be separated by using a supercritical magnetic field.

With a tuning slug present additional information can be obtained on the observed frequency and Q change. This can be compared with the predicted change in frequency and calculated surface current density due to slugs of various diameter.

F. Hard Superconductor Experiments

The Parmenter[5] paper suggested observed magnetic field effects above H_c would be characteristic of alloys and hard superconductors. This can be verified with niobium and other hard superconductors used in resonant circuits. During this quarter plans were made and material received to fabricate niobium foil tanks on quartz substrates. The configuration is such that any foil superconductor capable of modest bending can be easily assembled for use in the VHF frequency range.

IV. CONCLUSIONS

The work of the second quarter has shown that the experiments which have been designed will yield the data required for the continuation of the investigation. Means exist for making measurements on lead-tin circuits which are tunable, can be evacuated, and are subject to changes in coupling of over 100db. The circuits will be coated or plated with varying compositions of the superconducting constituents which will shown the relative merits of performance and ease in fabrication of lead-tin alloys.

The configuration adopted will also permit a wide variety of basic physical measurements of the properties of the various materials of interest.

Extension of the measurements of hard superconductors in foil form will provide much needed information on the rf conduction processes in these materials.

V. PROGRAM FOR THE THRID QUARTER

The work of the third quarter will consist of experiments and analysis of data based on the efforts which have been made to date.

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VII. PERSONNEL

The technical staff consists of:

Project Director: William H. Hartwig
Approx. Man-Hours: 280
Education: BSEE 1947, W. Va. Univ., MEE 1949, Cornell Univ., PhD 1956, Univ. of Texas
Experience: Electronics and Solid State Applications.

Research Engineer: Roland Haden
Approx. Man-Hours: 240
Education: BSEE 1961, Arlington, MSEE 1962, Calif. Institute Tech. (University Fellow)
Experience: Texas Instruments Inc., Electronics design Engineer.

Research Engineer: George D. Arndt
Approx. Man-Hours: 160
Education: MSEE 1962, Mississippi State.
Experience: Graduate student in Electrical Engineering.

Research Engineer: Parker M. Loeffler
Approx. Man-Hours: 240
Education: BSEE 1962, University of Texas.
Experience: Computer programmer.
Graduate student in Elec. Eng'g.

Research Assistant: Robert L. Lindner
Approx. Man-Hours: 144
Education: Senior Elec. Eng'g. student.
Experience: Research laboratory assistant.

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Studies of inductance calculation proceeded to the point where the solution for a coaxial inductor in a closed cylindrical shield was obtained. The geometry is for current strips of zero thickness.

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